Application Report
SLVA113A – February 2002

Optimizing the Layout of the TPS546xx for Thermal Performance

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ABSTRACT

This application report examines the thermal performance of different layout techniques for the TPS5461x family of 6-amp, synchronous buck regulators. The TPS5461x family consists of the TPS54610, TPS54611, TPS54612, TPS54613, TPS54614, TPS54615, and the TPS54616. The TPS54610 has an adjustable output voltage, while the output voltages of the other devices in this family are fixed. This application note is also applicable to the TPS54672 tracking regulator. Factors examined include the use of thermal vias, the amount of copper used on the PWB, the solder connection of the PowerPAD™, and environmental conditions.

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1 Introduction

Thermal management of an electronic circuit board can be a daunting task. It usually requires knowledge of the major heat dissipaters in the system, the environmental conditions, some theoretical calculations, and some amount of guesswork. The goal of this application report is to eliminate some of the guesswork required for designing with the TPS5461x SWIFT™ family of synchronous buck regulators. The results presented in this report are also applicable to the TPS54672 tracking regulator.

The TPS5461x family of devices can provide over 6 amps of continuous output current from an input source in the range of 3 volts to 6 volts. Table 1 provides a summary of all the devices in the TPS5461x family. The devices in this product family come in a 28-pin TSSOP PowerPAD™ package. The PowerPAD package is what enables the TPS5461x to deliver high output currents in such a small footprint. By soldering the exposed lead frame on the bottom of the package directly to the PWB, the PowerPAD package provides a junction-to-ambient thermal impedance much lower than other standard packages of comparable size. Because the PWB acts as a heat sink for the PowerPAD package, the thermal performance of the TPS5461x is dependent on the PWB layout.

Table 1. TPS5461x Family Summary

Device	Output Voltage (Volts)
TPS54610	Adjustable
TPS54611	0.9
TPS54612	1.2
TPS54613	1.5
TPS54614	1.8
TPS54615	2.5
TPS54616	3.3
TPS54672	Tracking

2 Test Circuit Description

Test boards were designed to demonstrate the thermal effects of different layout techniques and environmental conditions. The same electrical circuit is used for all of the thermal tests presented in this report. Figure 1 shows the schematic of the test circuit, consisting of a TPS54615 and its associated external components.

For any given input voltage and load current, the power losses of every device in the TPS5461x family are virtually identical. As a result, replacing the TPS54615 with any of the other TPS5461x devices results in a nearly identical thermal response. Although all testing is performed with the TPS54615, the results are applicable to the entire TPS5461x family, as well as the TPS54672.

The dimensions, copper weight, and topside layout are the same for every test board evaluated in this report. Each board is 3 inches by 3 inches, with 1.5 ounces of copper on the top and bottom layers, and 0.5 ounces of copper on the internal layers. The layout of the top layer is shown in Figure 2. Factors that are varied for the different test boards include the pattern of vias under U1, the number of ground plane layers, the amount of copper on the back side of the board, the solder joint quality of the PowerPAD, and environmental conditions.

For any system, it is important to identify the major sources of power losses, and to quantify the losses generated by these components. There are two major sources of power losses in the thermal test circuit: the TPS54615 (U1) and the output inductor (L1). The losses in these components are plotted in Figure 3.

Because the inductor value in the test circuit is relatively high, the ac ripple current is small compared to the dc inductor current. Thus, the majority of the inductor losses are dc conduction losses, and independent of input voltage and switching frequency. While the inductor losses are comparably smaller than the TPS54615 losses, they still contribute to a rise in the board temperature, and consequently, a rise in the junction temperature of U1.

The TPS54615 generates a majority of the losses on the test circuit board. In Figure 3, the TPS54615 losses are plotted for both a 5-V and a 3.3-V input voltage. The losses are higher at lower input voltages because the lower drive voltage increases the drain-to-source resistance of the integrated FETs. The losses in U1 also increase slightly as the die heats up. The TPS54615 losses shown in Figure 3 are for a junction temperature of 125°C, representing a worst-case condition. These losses are lower at lower junction temperatures. The switching losses of the TPS5461x devices are extremely low compared to the conduction losses. As a result, the switching frequency has very little effect on the power dissipated in the IC. All test boards evaluated in this report are configured for a 550 kHz switching frequency.

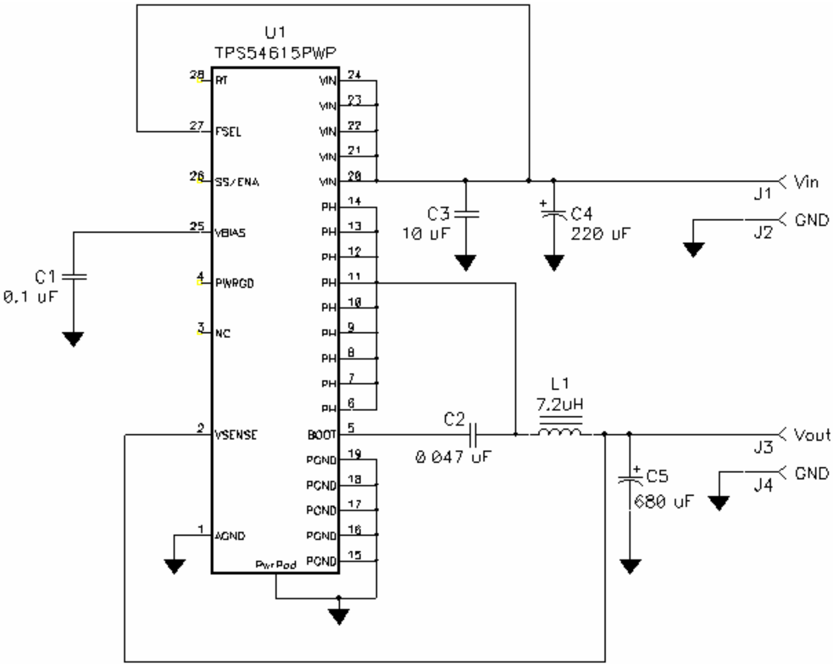

Figure 1. Test Circuit Schematic

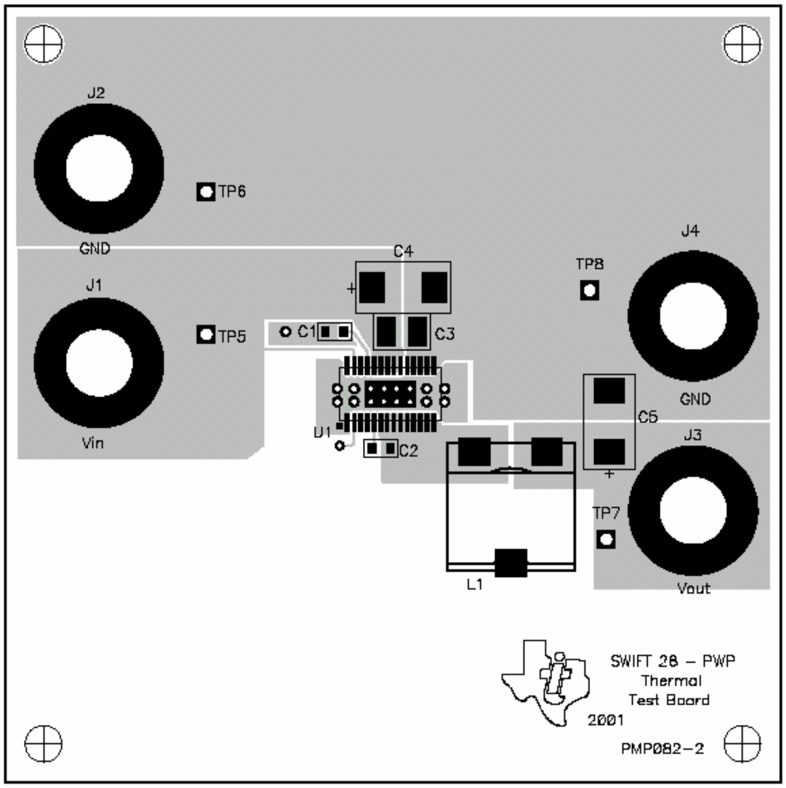

Figure 2. Top-Side Layout

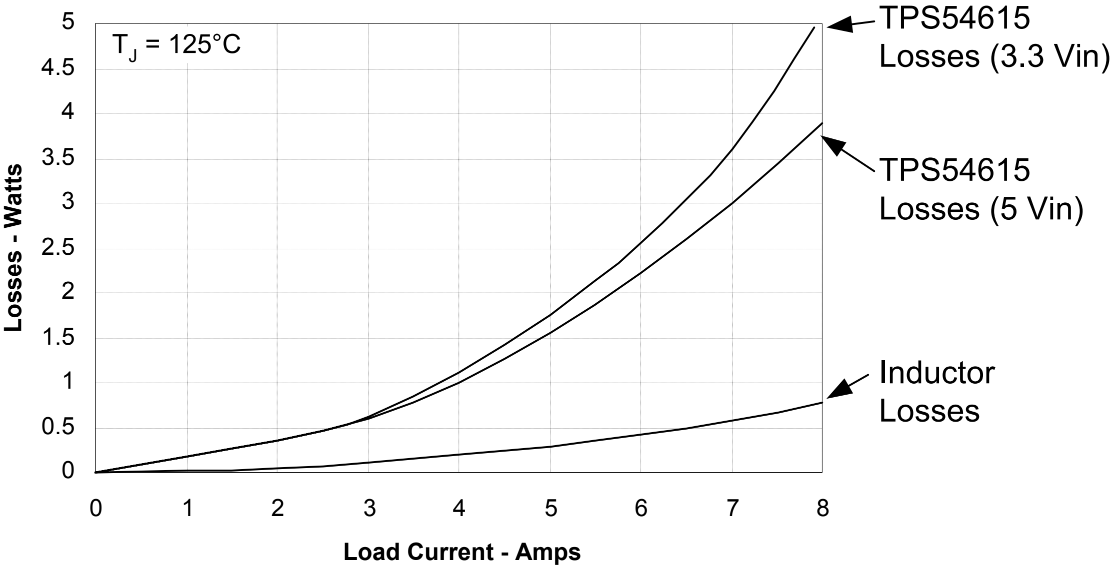

Figure 3. Test Circuit Component Losses

3 Thermal Vias

Vias placed underneath and near U1 help to pull heat away from the die. This effectively lowers the equivalent junction-to-ambient thermal impedance of the TPS54615. Four different via patterns were evaluated. These four patterns are shown in Figure 4. Each pattern consists of eight 13-mil diameter vias located directly underneath the PowerPAD, plus various amounts of 18-mil diameter vias located near the PowerPAD.

These thermal vias are connected on the on the top layer of the PWB to a copper plane that solders directly to the PowerPAD. The thermal vias are also connected to a ground plane on the bottom layer (backside) of the PWB. Some of the test boards also contain ground planes on internal layers. These internal ground planes are also connected to the thermal vias and act as heat sinks for the IC. The cross-section shown in Figure 5 is an example of the connections between the vias and the ground planes.

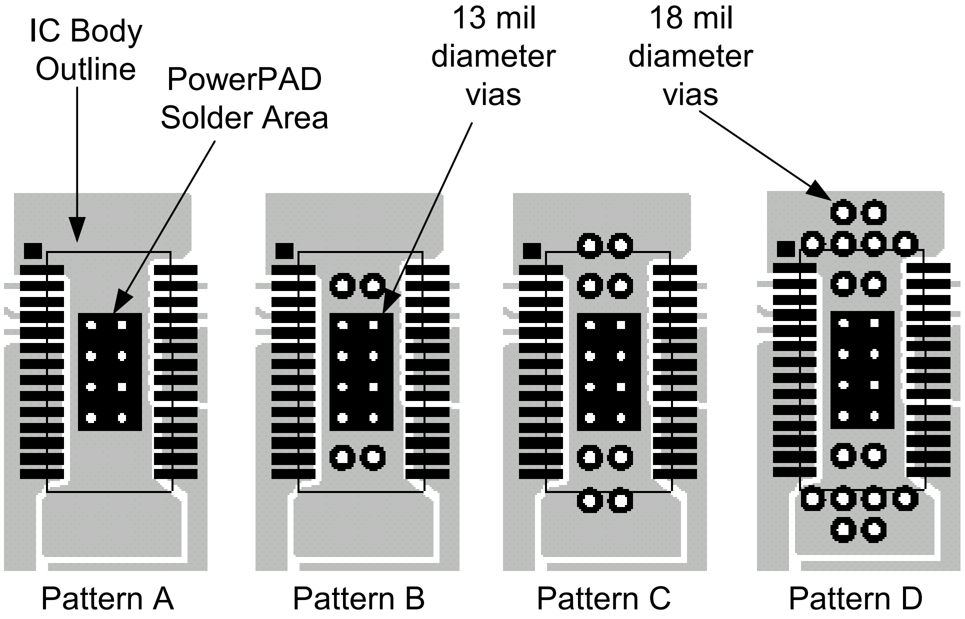

Figure 4. Thermal Via Patterns

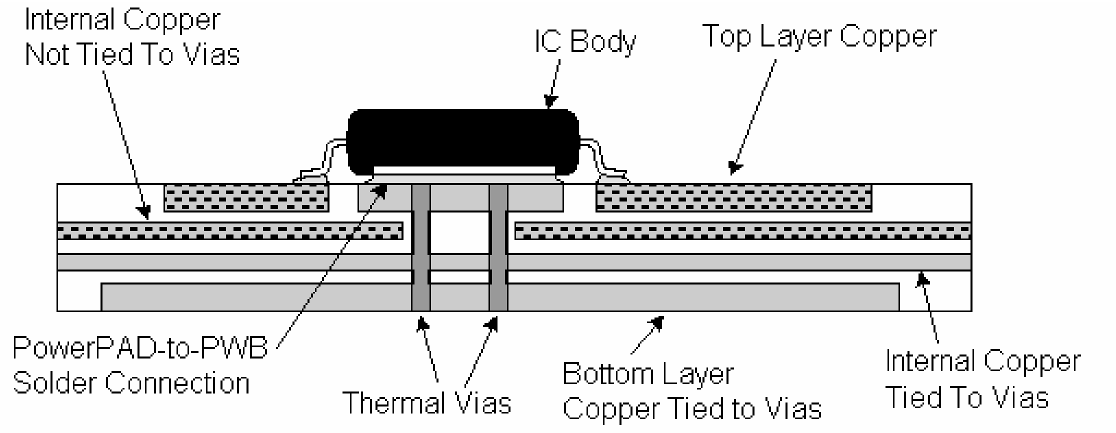

Figure 5. PWB Cross-Section

Figure 6 shows the junction temperature versus the load current for the different via patterns with a 5-volt input and a 25°C ambient temperature. The test results in Figure 6 were obtained from a multi-layer board, with two internal ground planes. By comparison, Figure 7 shows the same information for a multilayer board with a single internal ground plane. With an effectively smaller heat sink, the heat flow through the vias is less. As a result, the number of vias has less of an impact on the junction temperature.

A law of diminishing returns exists with regards to the number of thermal vias. As the number of vias is increased, the addition of each new via has less of an impact on the junction temperature of the IC. The TPS5461x data sheets recommend via pattern B (Figure 4). This via pattern consumes essentially the same amount of board space as the IC itself, while lowering the junction to ambient thermal impedance. Additional vias should be added as board space allows, especially at higher ambient temperatures.

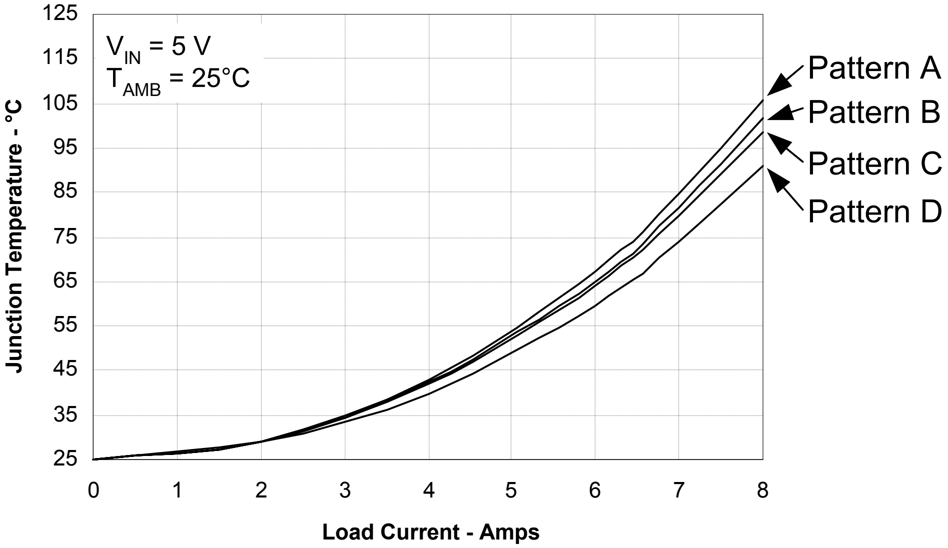

Figure 6. Via Pattern Comparison With Two Ground Planes

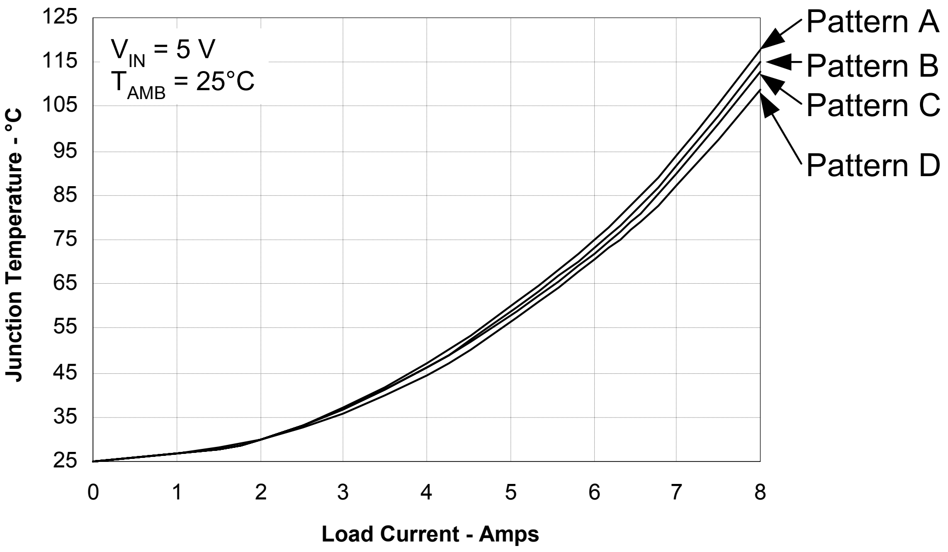

Figure 7. Via Pattern Comparison With One Ground Plane

4 Ground Planes

The amount of copper, and subsequently the number of ground planes in the PWB, play an important part in lowering the junction temperature of the IC. With more copper tied directly to the thermal vias, the junction temperature is lower. Figure 8 shows the effect of using different amounts of copper with via pattern B. The difference between using one ground plane and three ground planes results in nearly a 25°C difference in junction temperature with 8 A of load current. Using a larger single ground plane or a heavier copper weight also decreases the junction temperature. It is important to remember that the test board dimensions are only 3 inches by 3 inches, which is much smaller than most applications.

From a thermal standpoint, the worst-case condition is a two-layer board with a limited amount of copper on the backside of the board. Figure 9 compares the junction temperature of two layer boards with different amounts of copper on the backside (bottom layer). Via pattern B is used on the boards of Figure 9. With copper covering the entire 9 square inches of the backside of the board, the junction temperature is only 70°C at 6 amps. By comparison, with only 1 square inch of copper, the junction temperature is 84°C at 6 amps. In both cases, the junction temperature remains well below the 125°C maximum junction temperature limit with 6 amps of load current. However, the board with only 1 square inch of copper is limited to 7.4 amps of current at an ambient temperature of 25°C due to the insufficient amount of heat sinking.

At elevated ambient temperatures, the 125°C maximum junction temperature of the TPS54615 can limit the maximum load current if an insufficient amount of copper is tied to the thermal vias. This is illustrated in Figure 10, which displays the safe operating area (SOA) of four different test boards. The SOA is a plot of the ambient temperature that results in a 125°C junction temperature at a given load current. Each test board in Figure 10 uses via pattern B. These results suggest that all of these test boards perform adequately at 6 amps with ambient temperatures below 60°C.

The effect of copper volume on the thermal performance can also be summarized by approximating the junction-to-ambient thermal impedance for each of the test boards shown in Figure 10. This is shown below in Table 2.

Although the TPS5461x data sheets describe these devices as 6-A converters, operation at loads greater than 6 A are possible as long as the junction temperature never exceeds 125°C. In addition, care must be taken to ensure that the output inductor does not saturate due to the higher currents and higher temperatures.

Table 2. Thermal Impedance of Test Boards

Number of Internal Ground Planes	Copper Area on Bottom Layer	Junction-to-Ambient Thermal Impedance (°C/W)
2	3 in. X 3 in.	18.2
1	3 in. X 3 in.	20.5
0	3 in. X 3 in.	24.0
0	1 in. X 1 in.	29.0

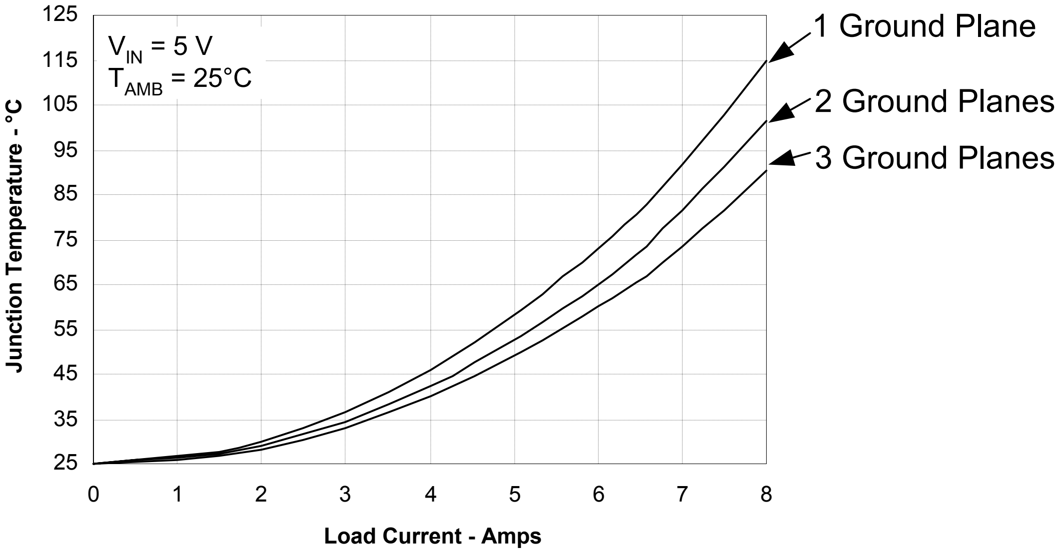

Figure 8. Ground Plane Comparison With Via Pattern B

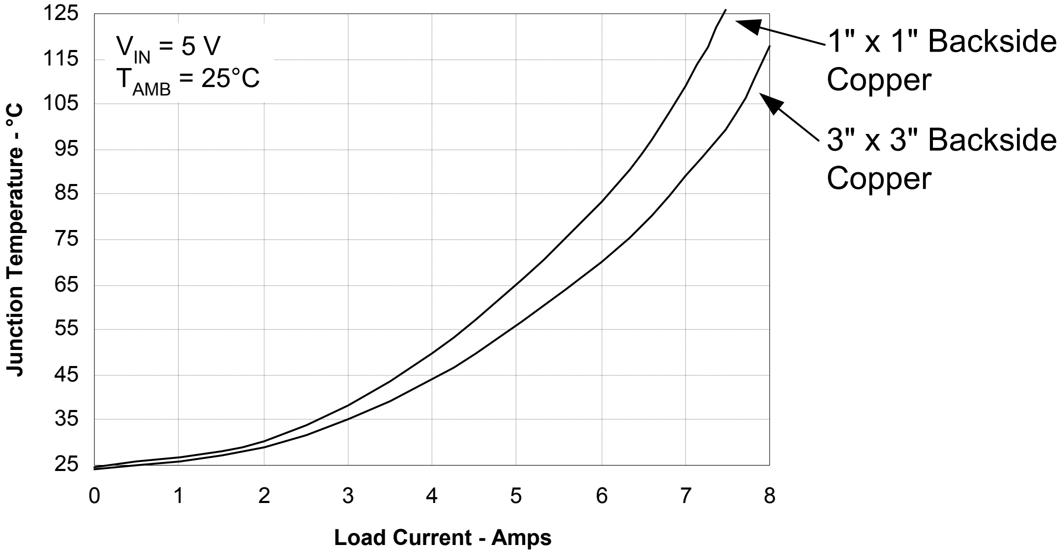

Figure 9. Two-Layer Boards With Different Amounts of Copper

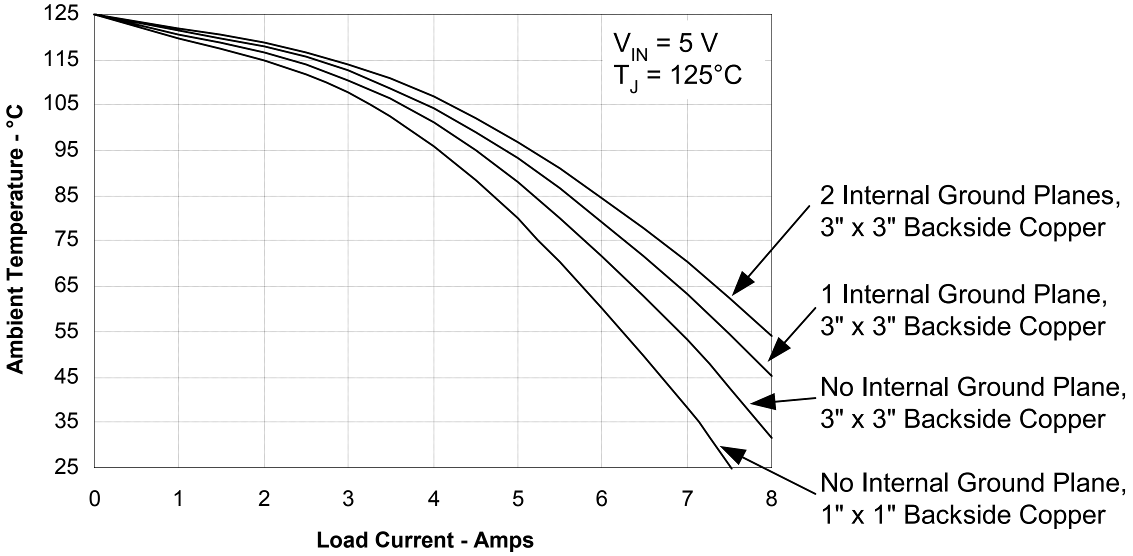

Figure 10. Effect of Copper Volume on SOA

5 Other Factors

Of course, numerous other factors affect the thermal performance of the TPS5461x devices. Some of these factors include the rate of air flow, input voltage, and heat generated by other components in the system.

Obviously, higher velocities of air flow help to cool the TPS5461x devices. To maximize the effectiveness of a forced-air cooled system, the airflow near the TPS5461x should be kept free from obstructions. Figure 11 displays the effect of using a 200-LFM airflow to help cool the TPS54615. A two-layer test board using via pattern B, with one square inch of copper on the backside is used in Figure 11. This example demonstrates that, using a minimal amount of copper, the TPS54615 can operate with 6 A of load current at an ambient temperature of 80°C.

At lower input voltages, the drive voltage for the internal MOSFETs of the TPS5461x is limited. Because of this, the drain-to-source resistance of the MOSFETs increases as the input voltage decreases. As a result, the power losses and junction temperature are higher at lower input voltages. This effect is illustrated in Figure 12, which shows the SOA with a 3.3-V input for the same test boards used in Figure 10. With a 3.3-V input, the copper volume becomes critical at ambient temperatures above 50°C for load currents above 6 A.

Other system components that dissipate significant amounts of heat elevate the board temperature; this also elevates the junction temperature of the TPS5461x. Thermal analysis of a complete system can be quite tedious and is beyond the scope of this application report. As a general rule, major heat dissipaters should be spaced apart in order to spread the heat across the board. Other heat sources are less of a concern when the TPS5461x is operated well within its SOA. In systems where the TPS5461x is operated near the limits of the SOA, system-level thermal testing may need to be performed, depending on the system safety and reliability requirements.

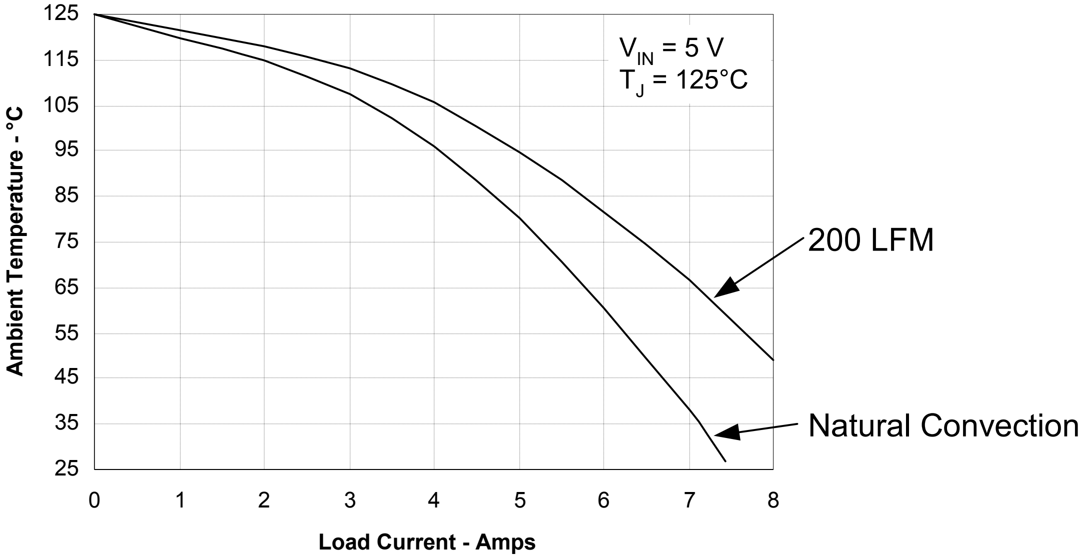

Figure 11. Effect of Air Flow on SOA

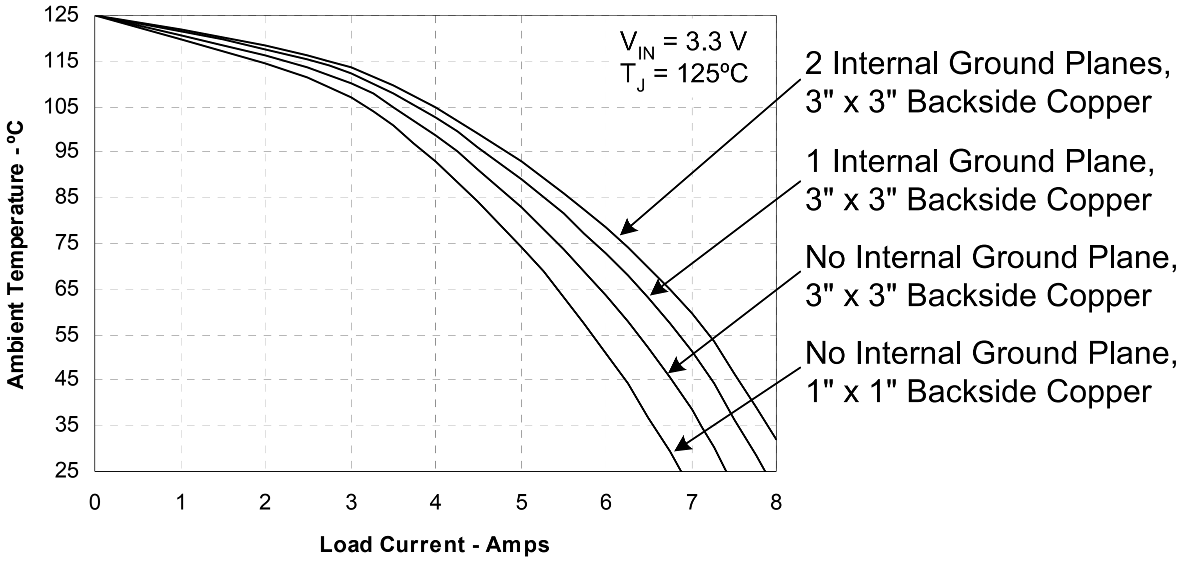

Figure 12. SOA With 3.3-V Input

6 PowerPAD Solder Joint

The PowerPAD enables the TPS5461x to deliver 6 A of load current in a small package. In order to deliver the 6-A rated current, a good solder joint is critical on the PowerPAD. The bulk of the TPS5461x power losses are conducted through the PowerPAD to the PWB. A poor solder joint on the PowerPAD raises the thermal impedance between the board and the PowerPAD and forces more of the heat to flow through the leads of the IC. Other studies have shown that at least 50% solder coverage on the PowerPAD is critical for proper thermal performance.

The effect of having no solder connection on the PowerPAD is shown in Figure 13. The amount of copper in the board does not greatly affect the SOA when PowerPAD is not soldered. With no PowerPAD solder connection, the maximum current at 85°C ambient temperature is limited to 3.7 A.

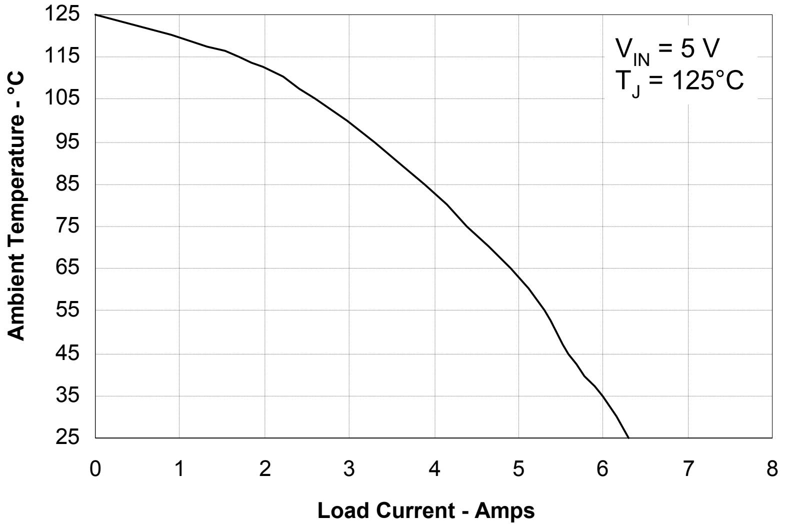

Figure 13. SOA With PowerPAD Not Soldered

7 Conclusions

Many factors affect the thermal performance of the TPS5461x devices. The test results presented in this application note can be used as a guide in predicting the TPS5461x thermal performance in most applications. In particular, the SOA curves and thermal impedances shown above can be quite useful for determining a minimal amount of copper required for a design. The following list provides a summary of design tips for maximizing the TPS5461x thermal performance.

- Use the recommended land pattern provided by the device data sheets.
- Use additional thermal vias as space allows.
- Ensure a good solder joint on the PowerPAD.
- Maximize the amount of copper connected to the PowerPAD through the thermal vias.
- If the PWB is forced-air cooled, make sure the air flow across the TPS5461x is free from obstructions.
- Spread out the location of other major heat-dissipating components as much as possible.

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